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Department of Psychology

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November 1979

GROUND-REFERENCED VISUAL ORIENTATION WITH IMAGING DISPLAYS: FINAL REPORT

Stanley N. Roscoe

Prepared For:

Air Force Office of Scientific Research
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report reviews a two-year investigation of problems related to the accurate judgment of size and distance as required of pilots in flight. The experiments covered a broad spectrum of psychophysiological issues involving the measurement of visual accommodation and its correlation with various other dependent variables. The latter included a short-term memory task, physiological measures of autonomic balance, scores on a personality test of introversion-extraversion, and responses to a personal inventory questionnaire. Psychophysiological issues investigated included the size-distance invariance hypothesis, the moon illusion,

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night and empty-field myopia, the dark focus and its so-called Mandelbaum effect, the nature and locus of the accommodative stimulus, and possible relationships among accommodative responses, autonomic balance, and personality.

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"Thou flatterer! Do I not know beauty is altogether in the eye of the beholder, and that all persons do not see alike?"

General Lew Wallace of Indiana
<u>The Prince of India</u>
1893, p. 178

It (the moon illusion) is not due to physical causes outside the visual mechanism. It is not due to the greater brightness of the moon in elevation, when atmospheric haze is diminished. It depends on raising or lowering the eyes.

Edwin G. Boring of Harvard
<u>American Journal of Physics</u>
1943, p. 874

When the eye is fixated on a point in space, that point is sharply focused on the retina. All points nearer or farther than the fixated point are blurred. The blur circles formed for points not in focus have diameters that vary ... as a function of the distance between the fixated point and the point not fixated.

The discrimination of the clearly focused image from the blurred image probably serves as a distance cue, although the process of discriminating must be quite complex and certainly has never been adequately investigated. Presumably such factors as the discrimination of detail and retinal image size combine with the subjects' reactions to provide the cue.

Clarence H. Graham of Columbia
<u>Handbook of Experimental Psychology</u>
Stevens (Ed.), 1951, pp. 882-883

BACKGROUND

A research program at the University of Illinois, sponsored by the Air Force Office of Scientific Research, started as an investigation of certain evidently related misperceptions experienced by pilots flying airplanes and airplane simulators by reference to periscopes and other dynamic image projection systems (Roscoe, Hasler, and Dougherty 1966; Palmer and Cronn 1973). Imaged objects such as airport runways appear smaller and farther away than objects subtending the same visual angles viewed directly; pilots making landing approaches tend to come in too high and land long and hard (Roscoe 1979). Our investigation has uncovered clues that have led us far afield from airplanes and airports and into the realm of basic psychophysical and psychophysiological research.

This two-year program descended from an abortive and unpublished effort at the University of Illinois in the early 1970s by a graduate student with the unlikely name of Gleason Snashall. When Gleason discovered the size-distance invariance hypothesis in the literature (Weintraub and Gardner 1970), he developed a computer program to show that an object subtending a given visual angle must appear smaller than lifesize if it appears nearer than it really is; hence, an airport scene imaged on a nearby screen (or viewed through a collimating field lens) must appear smaller than lifesize, thereby causing pilots to overshoot.

For Gleason the problem was solved, but his logic failed to explain the phenomenon to my satisfaction; indeed, Gleason made me mad, and I resolved to pursue the investigation personally at the earliest opportunity. With support from the National Aeronautics and Space Administration, Robert J. Randle and I conducted a series of studies at Ames Research Center during 1975 and 1976 (Roscoe, Olzak, and Randle 1976; Roscoe 1977; Roscoe and Benel 1978; Roscoe 1979; Randle, Roscoe, and Petitt in press). These studies all involved the automatic covert measurement of visual accommodation using an infrared tracking optometer developed for NASA by Cornsweet and Crane (1970).

The experiments ranged from measurements of the apparent sizes of discs subtending equal visual angles at different distances to the tendencies of pilots to undershoot or overshoot landing approaches when viewing dynamic computer-generated night visual scenes. There is a strong correlation between apparent size and visual accommodation distance and a weaker interaction between overshoot/undershoot judgments and accommodation to real images (but not to virtual images); other things being equal, the more distant the eyes accommodate, the larger an object of fixed angular size appears. However, the eyes do not obediently accommodate to the distances of foveally presented stimuli (as investigators often assume); in fact, eyes focus stimuli only well enough for the required discrimination.

APPARATUS

Concurrently with the Ames studies, equipment was being developed by Oskar Richter at the University of Illinois (under an earlier contract from the Air Force Office of Scientific Research) for use in the present program. This equipment included a viewing system colloquially referred to as "the moon machine." This device projects a collimated disc subtending a 0.67-degree visual angle onto a combining glass through which a subject can view any 45 x 45-degree stimulus scene (Figures 1 and 2). A comparison disc of variable diameter can be viewed alternatively by the insertion of a mirror on a sliding assembly, thereby allowing a subjective matching with the apparent size of the collimated "moon" seen against various backgrounds (à la Kaufman and Rock 1962).

Also alternatively, a subject can view the flowing speckle pattern produced by a laser optometer (of the type developed by Leibowitz and Hennessy 1975) superposed on any stimulus scene by means of a small combining glass immediately in front of the subject's eye. The operation of this system is described in greater detail by Iavecchia, Iavecchia, and Roscoe (1978) and by Benel (1979). It provides an absolute though subjective measure of visual accommodation in diopters (D), a scale inversely related to the distance to which the eye is focused (D = 1/distance in meters). The measurements obtained correlate highly with those of a polarized vernier optometer developed and used by Simonelli (1979a) later in the program.

Simonelli's optometer employs an old principle attributed to Scheiner (see Duke-Elder 1970, p. 155), described by Moses (1971), and more recently advanced by consultant Robert T. Hennessy (personal communication). In Simonelli's words, referring to Figure 3:

> Using two pairs of perpendicularly oriented polarizing filters, the retinal image of a viewed object--in this case, a horizontal bar--will split when the retina is not conjugate with the plane of that bar. Likewise, the image will be whole when the retina is conjugate with the bar. This is an application of the Scheiner principle, . . . whereby one image (here, one half of the bar) is directed through the upper half of the pupil, and another image (the other bar half) is directed through the lower half.
>
> This direction of bar halves through different portions of the pupil is accomplished by creating bar-segment images whose light rays are of different polarities (indicated in the figure by the direction of the parallel lines in the filters). The left half of the target bar, for instance, is vertically polarized. Such rays will pass through the upper portion of the next pair of filters (with some absorption loss), as the polarities of the light and filter are identical. These vertical rays, however, cannot pass through the horizontal filter below.

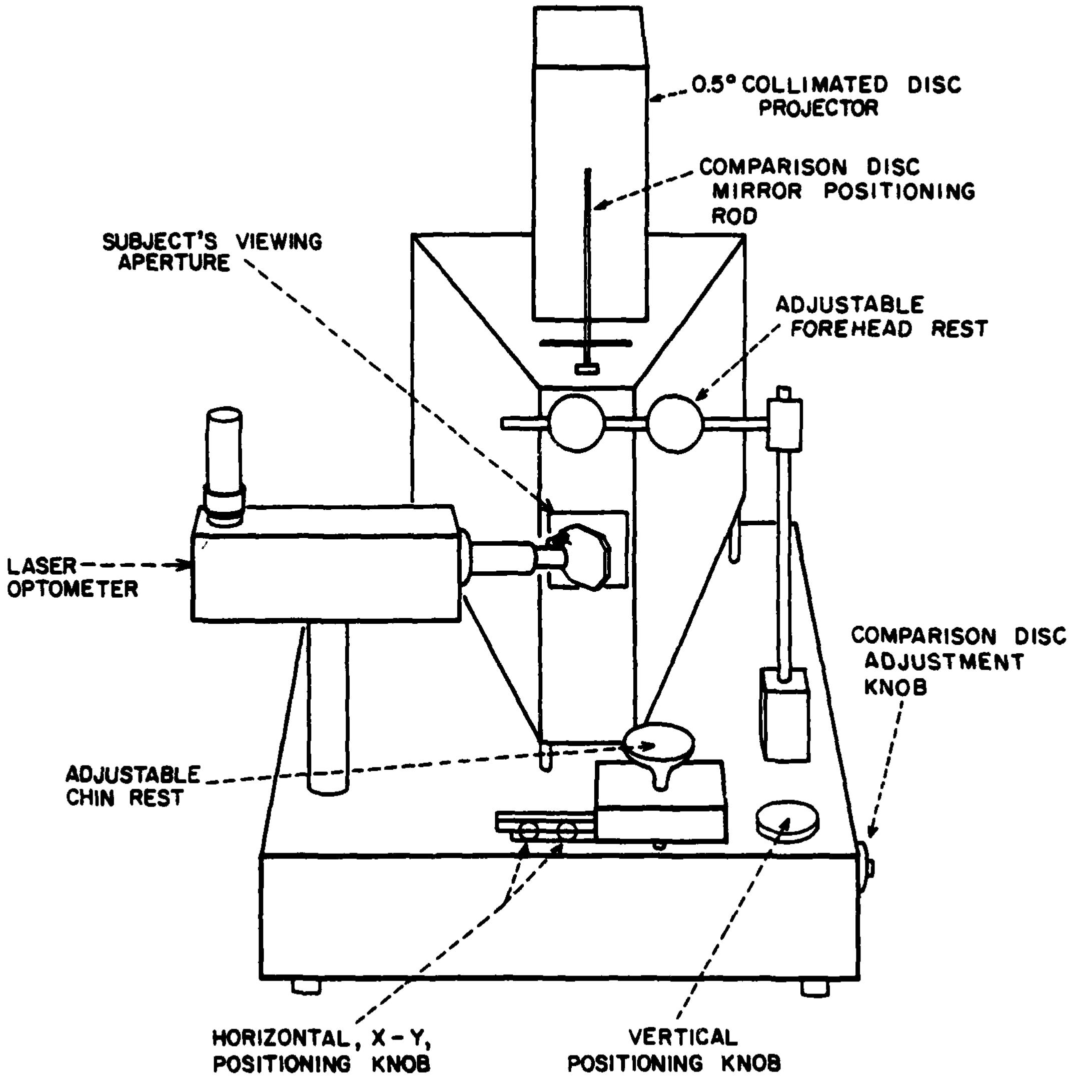

Figure 1. The Illinois "moon machine" and laser optometer used in experiments involving measurement and correlation of the apparent size of a simulated lunar disc and visual accommodation distance.

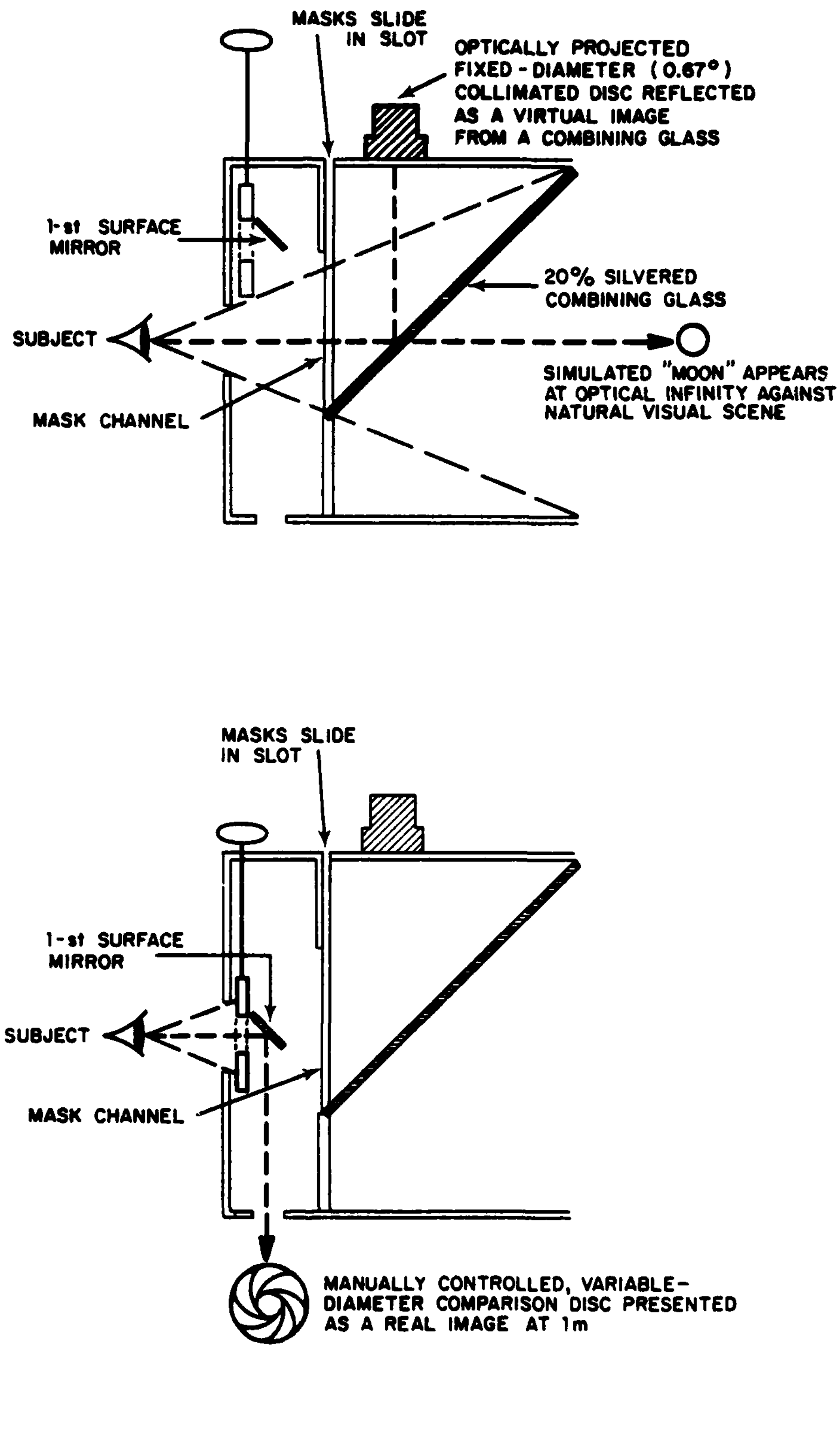

Figure 2. Cutaway schematic diagrams of the "moon machine" showing the presentation of the collimated lunar disc (above) and the variable-diameter uncollimated comparison disc (below).

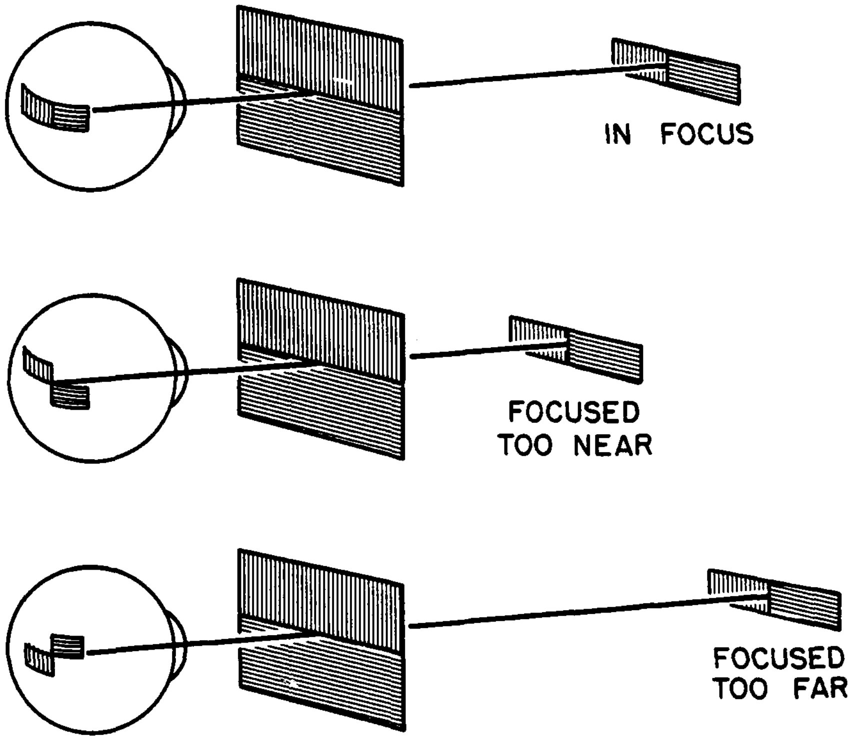

Figure 3. Diagram illustrating the use of orthogonally polarized filters to implement the Scheiner principle in Simonelli's polarized vernier optometer. An image polarized in one direction enters the eye through the upper half of the pupil; an image polarized orthogonally enters through the lower half.

Consequently, when this second pair of filters is aligned to "split" the pupil in half, the vertically polarized rays from the left portion of the target bar enter only the upper half of the pupil. Similarly, the image of the right half of the bar enters only the lower half of the pupil. When the eye is focused on the bar, both halves will "meet" at the retina and reform the whole bar. Moreover, one half will shift relative to the other when the eye is focused in front of or behind the stimulus bar. The amount and direction of the shift are related to the amount and direction of the focal error.

EXPERIMENTAL INVESTIGATION

Between 1977 and 1979, eight graduate students at the University of Illinois conducted seven experimental investigations, some involving more than one experiment. These studies are described in the following technical reports, the first three issued by the Department of Psychology, University of Illinois at Urbana-Champaign, and the last four by the Behavioral Engineering Laboratory, New Mexico State University:

Iavecchia, J. H., Iavecchia, H. P., & Roscoe, S. N. The moon illusion: Apparent size and visual accommodation distance (Tech. Rep. Eng Psy-78-4/AFOSR-78-3). Urbana-Champaign, IL: University of Illinois, Department of Psychology, 1978.

Benel, R. A., & Benel, D. C. R. Accommodation in untextured stimulus fields (Tech. Rep. Eng Psy-79-1/AFOSR-79-1). Urbana-Champaign, IL: University of Illinois, Department of Psychology, 1979.

Simonelli, N. M., & Roscoe, S. N. Apparent size and visual accommodation under day and night conditions (Tech. Rep. Eng Psy-79-3/AFOSR-79-3). Urbana-Champaign, IL: University of Illinois, Department of Psychology, 1979.

Benel, R. A. Visual accommodation, the Mandelbaum effect, and apparent size (Tech. Rep. BEL-79-1/AFOSR-79-5). Las Cruces, NM: New Mexico State University, Behavioral Engineering Laboratory, 1979.

Gawron, V. J. Eye accommodation, personality, and autonomic balance (Tech. Rep. BEL-79-2/AFOSR-79-6). Las Cruces, NM: New Mexico State University, 1979.

Simonelli, N. M. The dark focus of visual accommodation: Its existence, its measurement, its effects (Tech. Rep. BEL-79-3/AFOSR-79-7). Las Cruces, NM: New Mexico State University, Behavioral Engineering Laboratory, 1979.

Hull, J. C., Gill, R. T., & Roscoe, S. N. Locus of the stimulus to visual accommodation: Where in the world, or where in the eye? (Tech. Rep. BEL-79-5/AFOSR-79-9). Las Cruces, NM: New Mexico State University, Behavioral Engineering Laboratory, 1979.

An eighth technical report, issued by the University of Illinois, was based on data collected in 1976 by Lynn A. Olzak and Donna Miller at Ames Research Center:

Roscoe, S. N., & Benel, R. A. Is the eye smart or the brain forgiving? (Tech. Rep. Eng Psy-78-1/AFOSR-78-1). Urbana-Champaign, IL: University of Illinois, Department of Psychology, 1978.

A ninth report, issued by New Mexico State, described the principle, mechanization, and use of the polarized vernier optometer:

Simonelli, N. M. Polarized vernier optometer (Tech. Rep. BEL-79-4/AFOSR-79-8). Las Cruces, NM: New Mexico State University, Behavioral Engineering Laboratory, 1979.

The experimental investigations covered a broad spectrum of psychophysiological issues involving the measurement of visual accommodation and its correlation with various other dependent variables. The latter included judgments of apparent size, visual acuity discriminations, performance on a short-term memory task, physiological measures of autonomic balance, scores on a personality test of introversion-extraversion, and responses to a personal inventory questionnaire. Psychophysiological issues investigated included the size-distance invariance hypothesis, the moon illusion, night and empty-field myopia, the dark focus and its so-called Mandelbaum effect, the nature and locus of the accommodative stimulus, and possible relationships among accommodative responses, autonomic balance, and personality.

Apparent Size and Accommodation to Visible Texture

The Ames studies had established a reliable correlation between apparent size and accommodation to targets at distances up to 4 meters. Pilots flying airplanes by contact visual reference view objects at far greater distances. A convenient way to study perceptual and accommodative responses to distant scenes is to use a technique developed by Kaufman and Rock (1962) to quantify the moon illusion. By superposing a collimated disc of light on a natural outdoor scene and providing an adjustable-diameter disc nearby, a surprisingly accurate estimate of the apparent size of a distant object ("the moon") can be obtained. This technique was used by Joyce and Helene Iavecchia.

In their first experiment, the Iavecchia sisters had subjects view the collimated moon against the scenes from corresponding windows of the third through the eighth floors of the psychology building looking eastward across the Urbana-Champaign campus. As shown in Figure 4, the apparent size of the moon increased from the third through the sixth floors and decreased thereafter. Although accommodation was not measured in this experiment, the foveal textural stimuli visible from the various elevations appeared at distances ranging from about 30 meters (the roof of a nearby sorority house) to more than 1000 meters (trees and buildings across the Urbana campus).

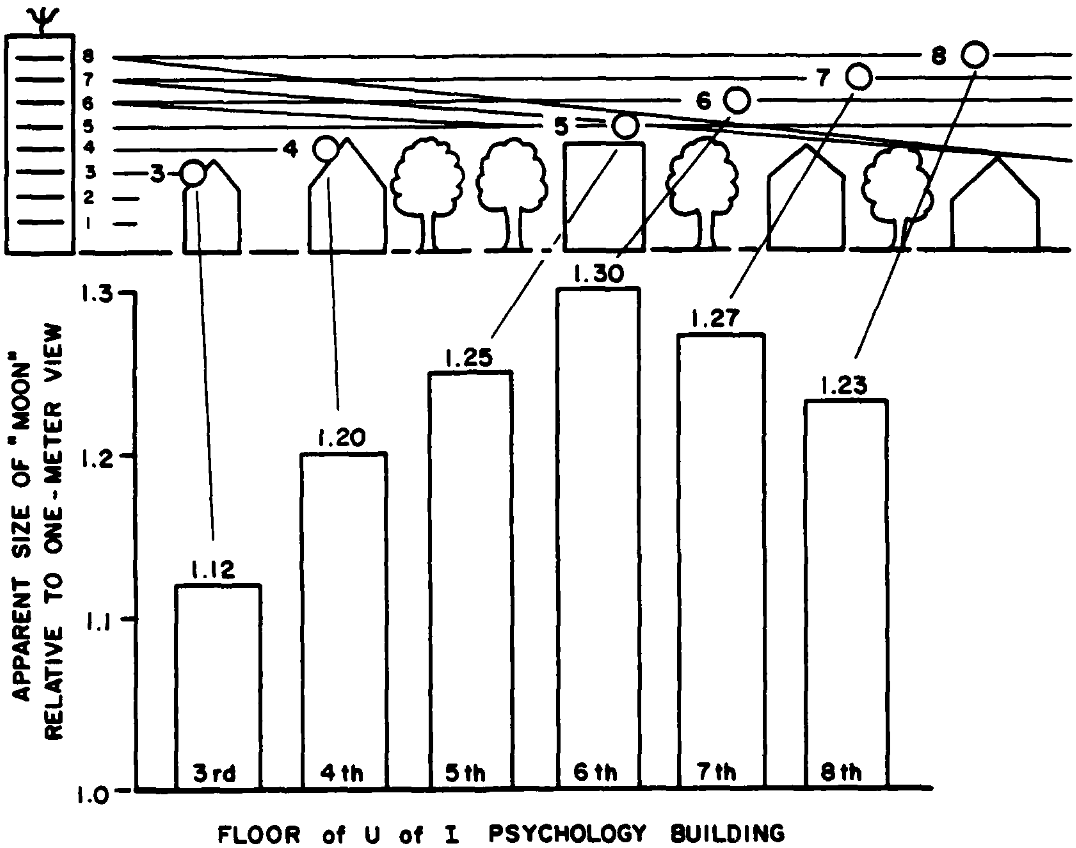

Figure 4. Apparent diameter of the simulated moon, when viewed from different floors of the psychology building, expressed as ratios of its apparent diameter when projected onto a newspaper at one meter.

In a second experiment from the sixth-floor elevation, the distance and angular depression of visible texture were systematically manipulated by use of a series of masks, as illustrated in Figure 5. In this experiment visual accommodation was measured with a laser optometer and correlated with subjective judgments of the apparent size of the collimated moon projected just above the distant horizon. A systematic relationship ($\underline{r} \approx .9$) was found between accommodation distance and the apparent size of the moon, a finding quite consistent with the hypothesis that accommodation varies with the locus of textural stimuli all of which are well beyond what is nominally though of as "optical infinity," as shown in Figure 6.

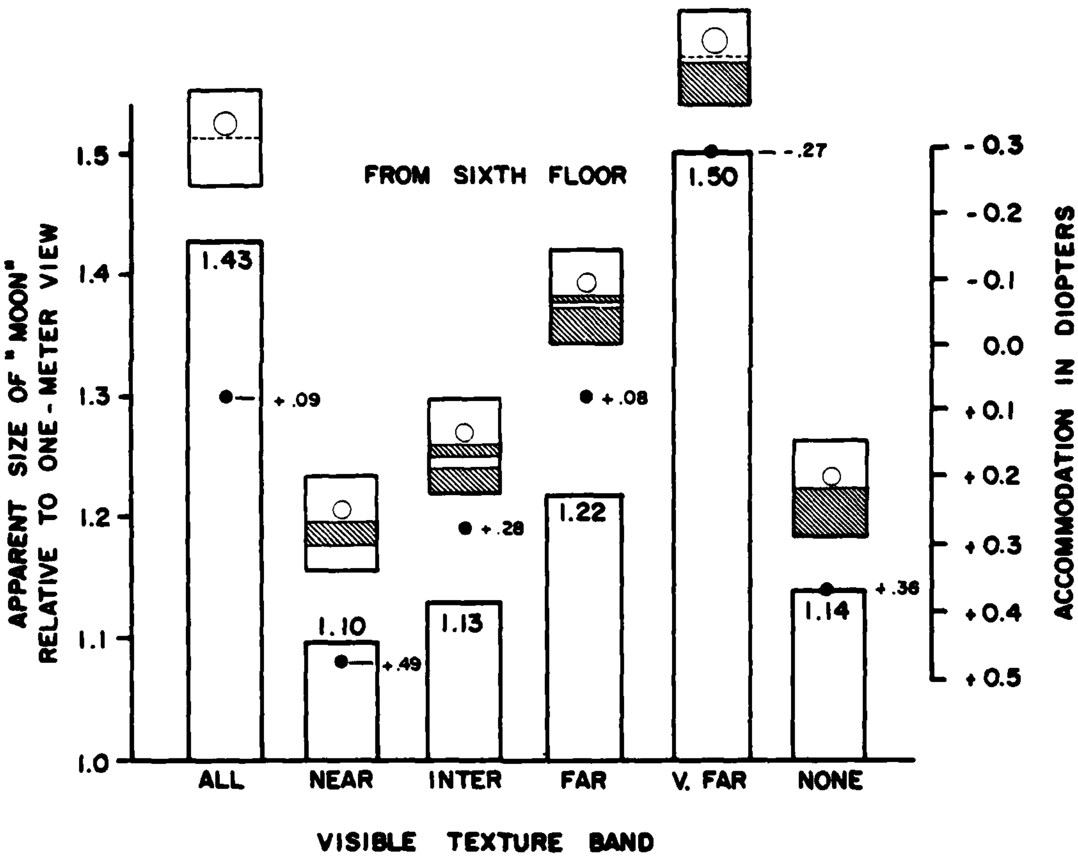

Figure 5. Apparent diameter of the moon, expressed as ratios of its apparent diameter when projected onto a newspaper at one meter, and associated visual accommodation distances, expressed in diopters, when various horizontal bands of texture are visible in the natural scene from the sixth floor (adapted from Iavecchia, et al., 1978).

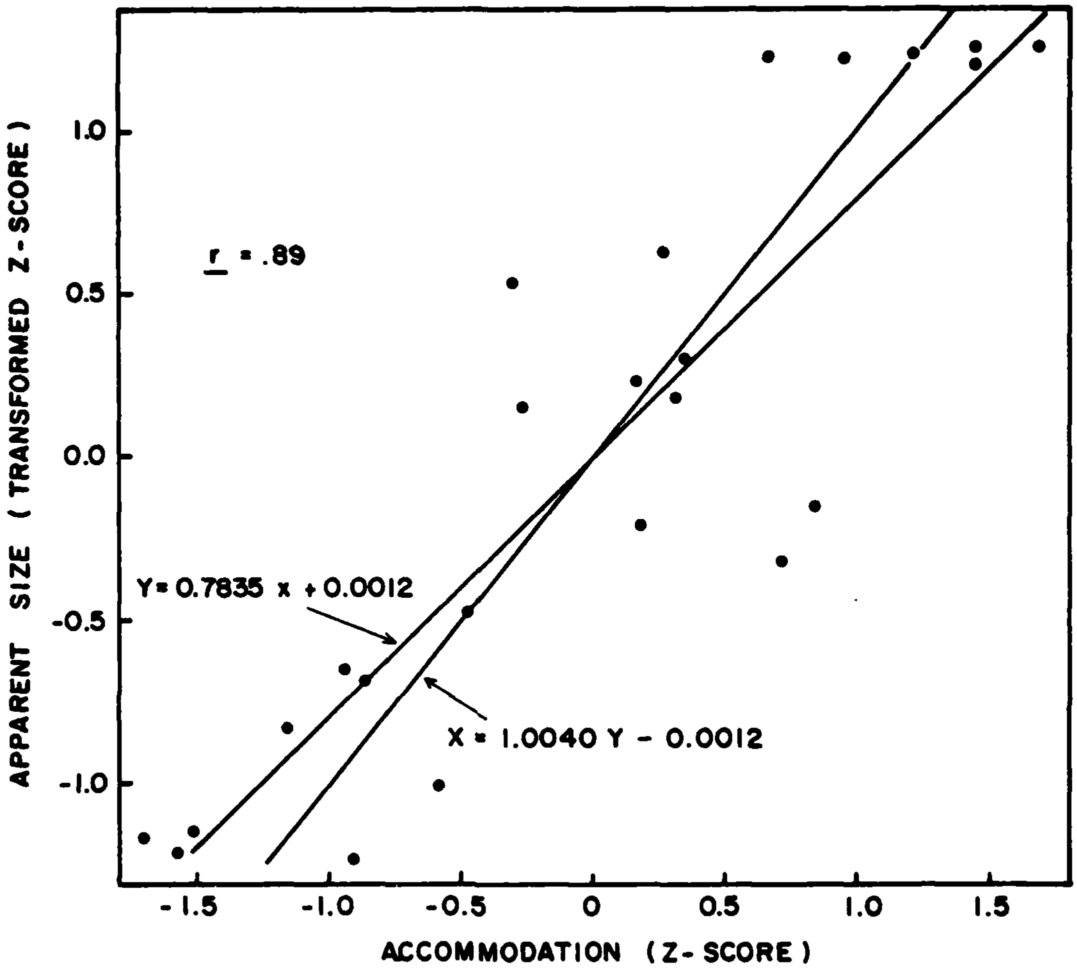

Figure 6. Scatter plot of the relationship between the apparent size of the moon, expressed as a transformed Z-score (specifically, 1.23 Diameter - 0.47 Diameter^2 + 0.47) and visual accommodation distance, expressed as a Z-score (Iavecchia, et al., 1978).

The Iavecchia experiments established the relationship between apparent size and accommodation for distances far beyond those investigated in the earlier Ames studies, but they also raised additional questions that called for further investigation. The nature and locus of the accommodative stimulus were not untangled and in fact were still totally confounded. Nicholas Simonelli investigated the effects of the reduced nature of textural stimuli under night as opposed to daylight viewing conditions (Simonelli and Roscoe 1979), and Jan Hull and Richard Gill (with assistance from Thomas Bolitho) investigated the locus of the accommodative stimulus (Hull, Gill, and Roscoe 1979).

There is conclusive evidence of functional myopia in the absence of a proximal textural gradient as in flight (empty-field myopia) or the reduced gradient in the relative darkness of night. Simonelli conducted an experiment similar to the Iavecchia manipulations but from the roof of the eight-story psychology building both in the daylight and at night. In the daylight the nearest textural stimulus appeared at about 100 meters with "empty space" intervening. At night the lights of the city were visible at an even greater distance. The masking manipulations had relatively little effect on the myopic accommodative responses and apparent size judgments, but the correlations between accommodation and apparent size were virtually identical to those obtained by the Iavecchias in daylight ($\underline{r}$ = .9) and slightly lower at night ($\underline{r}$ = .7).

Where in the World or Where in the Eye?

In the Iavecchia experiments the distance to dominant textural stimuli and their retinal locus were confounded. In the first experiment (in which accommodation was not measured), the distance to visible textural stimuli increased as the views progressed from the third through sixth floors, and the apparent size of the moon <u>increased</u> accordingly. From the sixth through eighth floors the dominant visible texture appeared farther and farther below the foveally presented collimated moon, which <u>decreased</u> in apparent size accordingly. In the second experiment (in which accommodation was measured), masks were used to obscure or reveal horizontal bands of texture whose absolute distance and angular depression from the foveal stimulus covaried inversely.

The subsequent experiments by Hull and Gill involved independent manipulations of retinal locus and absolute distance of stimuli, thereby helping to untangle the previous confounding but with a surprising result requiring further untangling. In their first experiment (employing three masks exposing near/low, intermediate, and far/high textural bands, respectively), the sixth-floor view across the Urbana campus was photographed (the same view used in the second Iavecchia experiment), and the color slide was rear-projected on a screen viewed by subjects through a large (25-inch diameter) collimating field lens immediately in front of the moon machine, as shown in Figure 7.

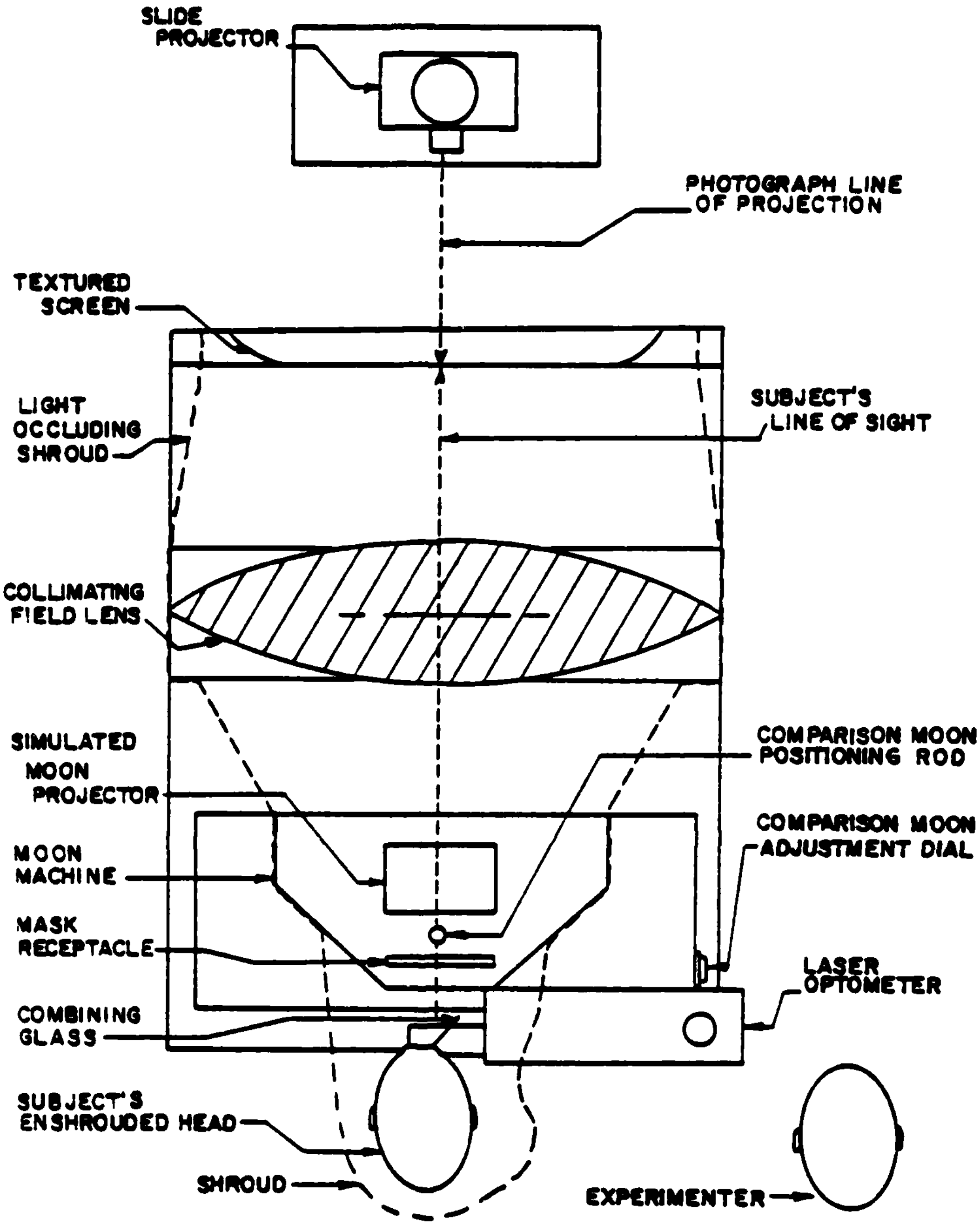

Figure 7. Arrangement of apparatus used by Hull and Gill. Subjects made judgments of the apparent size of the simulated moon when combined optically with collimated projections of a color photograph of the sixth-floor view of the Urbana campus through various masks. Associated visual accommodation distances were measured with a laser optometer.

This arrangement provided an image of the entire scene from "optical infinity," thereby allowing manipulation of the locus of retinal stimulation while holding "optical distance" constant. To assess the stimulus value of a two-dimensional photographic image of a three-dimensional real-world scene, a second set of accommodation and apparent-size measurements were made while the subjects viewed the simulated moon against the backlighted screen providing collimated texture through the various masks but no scenic image. To allow direct comparison of responses in these conditions to those in the second Iavecchia experiment, measurements of responses to the real-world sixth-floor scene were repeated for the eight subjects in this study.

Once again the mask manipulations resulted in differential shifts in accommodation, this time measured relative to the individuals' dark focus distances, and corresponding shifts in the apparent size of the moon. However, as shown in Figure 8, the absolute accommodation levels to either of the collimated two-dimensional stimulus views were highly myopic relative to those from the three-dimensional out-the-window scenes, and the magnitude of the moon illusion varied accordingly. Figure 8 shows the mean apparent size of the moon plotted against the mean accommodation level for the eight subjects in response to each of the three textural bands (masks) for each of the three scenes (views).

The correlation between these two sets of means is 0.97. Despite the orderliness of this relationship, inspection of the 72 individual points (3 masks by 3 views for each of 8 subjects) showed that apparent size and accommodation were not related in a purely linear fashion. As in the Iavecchia study, the apparent diameter of the moon increased disproportionately with outward accommodation expressed in diopters. Evidently the dioptric scale does not represent equal psychophysical units. As was done by the Iavecchias, the apparent-size scale was transformed, but in this case the reciprocal of the square of the linear dimension (the diameter of the moon) yielded the best-fitting linear relationship. This suggests that apparent area is a linear function of the focal distance of accommodation.

So far, so good. Visual accommodation and apparent size (when suitably transformed) bear a strong linear relationship when the retinal locus of a textured accommodative stimulus is varied systematically relative to a foveally presented untextured target object (the moon). This relationship holds even though the responses to collimated two-dimensional scenes are much nearer (in diopters) and smaller (in degrees) than corresponding responses to three-dimensional real-world scenes. But what happens when the absolute distance to visible real-world texture is varied while holding the retinal locus of the textural stimulus approximately constant?

To investigate this question, Hull and Gill partially replicated the first Iavecchia experiment, this time measuring accommodation. Using the intermediate mask that revealed a horizontal band depressed from the line-of-sight, subjects viewed the simulated moon above rooftops and treetops at successively increasing distances from the fifth-, sixth-, seventh-, and eighth-floor views across the Urbana campus, as illustrated in Figure 9. The mean size judgments and accommodative responses to this manipulation

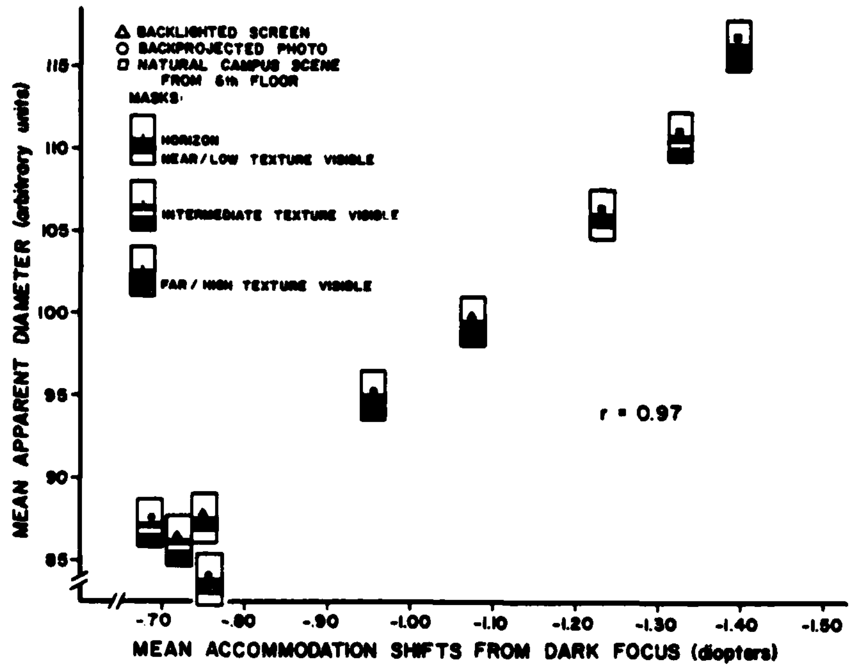

Figure 8. Mean apparent diameter of the simulated moon (in arbitrary units) as a function of the mean accommodation shift from individual dark focus levels for eight subjects viewing three textural bands (masks) for each of three scenes (views).

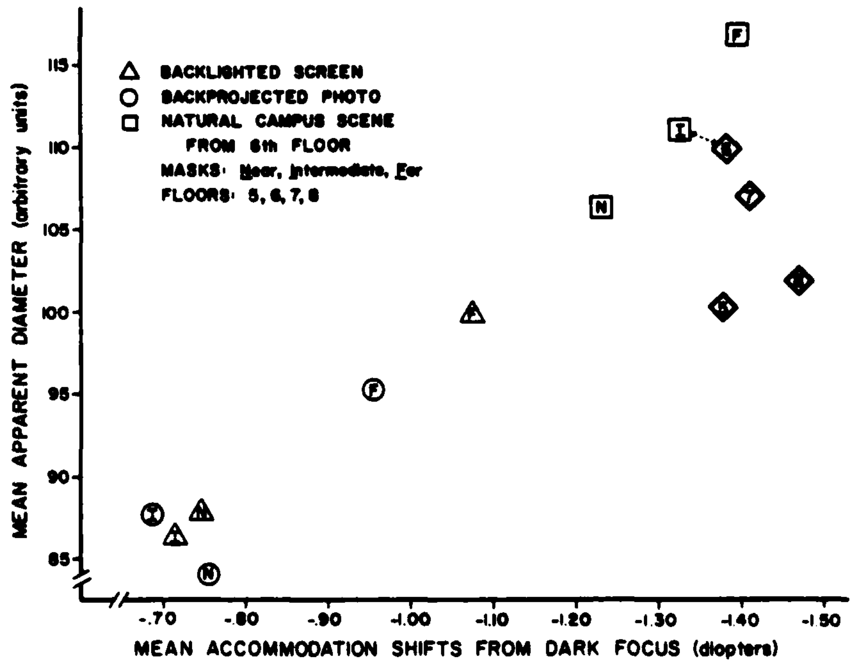

Figure 9. Mean apparent diameter of the simulated moon (in arbitrary units) plotted against mean accommodation shifts from individual dark focus levels for eight subjects viewing the campus vista through the intermediate mask from various floors of the psychology building. (Data points from Figure 8 are repeated for comparison.)

are superposed on the corresponding values from Figure 8 for the previous experiment by Hull and Gill. Neither apparent size nor accommodation varied reliably although apparent size tended to increase from the fifth- to sixth-floor views and decrease thereafter as observed in the first Iavecchia experiment.

On the surface it would seem that the retinal locus of a textured stimulus is the primary determinant of the accommodation response of the eye, but what then determines apparent size and distance? Clearly a more systematic and precise manipulation of the retinal locus and absolute distance of more uniform textural gradients is required to untangle this puzzle. Evidently from the earlier experiments eye accommodation is involved in some way in judgments of apparent size, but the nature of the involvement is far from clear. Accommodation must interact in some complex manner with other variables as yet not fully identified. Study of the problem continued.

Accommodation in Untextured Stimulus Fields

The background studies at Ames Research Center and all of the Illinois studies discussed so far involved textured visual stimuli, in most cases real-world vistas or photographic projections thereof. To understand the contributions of texture in determining the accommodative reflex, Russell and Denise Benel (1979) performed a series of experiments involving untextured stimulus fields. In their words:

> When textural cues are reduced through lowered illumination and contrast, night and empty-field or space myopia occur. Instrument myopia is typically attributed to viewing through small apertures. These myopias are referred to as anomalous because, contrary to the classical view, accommodation for near images occurs in the absence of...[textured stimuli]... (Leibowitz and Owens, 1978). An alternative theory of accommodation proposes that there is dual control of the ciliary muscle and the intermediate state reflects a passive return to a neutral balance point between these opposing systems. Although this alternative theory has been frequently proposed and subsequently denied, anatomical and physiological evidence has mounted making it difficult to reject (see Cogan 1937 for a review of the early evidence or Benel 1979 for an updated review).

Although there were reliable mean differences in accommodation to the various untextured stimulus manipulations employed by the Benels, the measured responses in all cases departed little from the individual subjects' resting accommodation distance or dark focus. As has been reported by many investigators, in the absence of adequate textural stimuli at distances other than the dark focus, little accommodation occurs, either inward or outward. The correlation between accommodation to any untextured stimulus and the dark focus is extremely high, typically in excess of 0.9.

Visual Accommodation, the Mandelbaum Effect, and Apparent Size

Russell Benel pursued the implications of the evident relationships between the large differences among the dark focus distances of different individuals and their judgments of apparent size as influenced by textural patterns of varying spatial frequency and acutance at varying distances. His studies involved the phenomenon that has become known as the "Mandelbaum effect." Mandelbaum (1960) observed that he and several of his friends were unable to read a sign from inside a screened porch although it was clearly legible when viewed directly. He also noted that the sign could be read through the screen if one moved closer or farther from it or moved the head from side-to-side.

Mandelbaum concluded that he and his friends were accommodating involuntarily to the screen rather than the sign, and Owens (1979) has subsequently demonstrated that the critical distance from a screen at which the effect occurs is the individual's dark focus distance. Benel proceeded to review the vast literature that might have a bearing on this phenomenon including anatomical and neurophysiological considerations, the long controversy over the single versus dual innervation by the parasympathetic and sympathetic branches of the autonomic nervous system (see Cogan 1937), and the so-called anomalous myopias--night, empty-field, and instrument. In Benel's words:

> Recent evidence has made it clear that earlier conceptions of visual functioning bear reexamination. Roscoe and Benel (1978) have noted two misconceptions that have misdirected psychologists for more than a century. The first concerns the misbelief that the eye's relaxed accommodation distance is at the far point, for the emmetrope at "optical infinity." This legacy has been passed down from Helmholtz (1867/1962, vol. 1, p. 360) who declared "when it [the eye] is focused for the far point, ... accommodation, therefore, is relaxed." Concomitant with this view is a single innervation theory of control of the ciliary muscle. Frequently, belief in single innervation obscured the need for verification of the far resting point and vice versa.
>
> The second closely related misconception has been the belief that the eye reflexively accommodates accurately to the distance of an object present in foveal vision. This latter belief is often implicitly assumed to hold in laboratory experiments on visual sensation and perception. The importance of these topics is apparent to psychologists because of their historical concern for the role of oculomotor adjustments in space perception (Baird, 1970). These oculomotor adjustments represent the initial response to distance and determine the clarity of the retinal image. This in turn, has a fundamental influence on perception and on the information derived from the stimulus. (Benel, 1979, pp. 1-2)

Benel then drew upon Hoffman, as translated by Ogle (1950, p. 10):

> ...Look with one eye, while the other is closed, at a window several meters away. Then hold one finger so close in front of the active eye that you have to accommodate on it with difficulty. As soon as this is done, the window shrinks and seems smaller than when one observes it without the effort of accommodation. Of course, a measuring rod behaves in precisely the same way if it is applied to the window at that time. Thus, the objective size of the window gives us no information as to the subjective size, either of the measuring rod or of the object--the window--that it measures. The spatial extent of objects does not give us any standard for the size of subjective, visual objects. (Benel, 1979, pp. 2-3)

Picking up on the work of D. Alfred (Fred) Owens at Pennsylvania State University (now at Franklin and Marshall College), Benel did four experiments that comprised his doctoral research. Owens had hypothesized that stimulus characteristics necessary to draw accommodation away from the dark focus include textural contrast peaks between the spatial frequencies of 5 and 14 cycles per degree of visual angle; any target containing only spatial frequencies outside the observer's optimum sensitivity range should not be an effective stimulus for accommodation. Either low-frequency targets, such as gross, blurred shapes, or high-frequency targets, such as small, sharp fixation points, would be poor accommodative stimuli.

Owens also proposed quantifying the effects of stimuli of varying spatial frequencies by optically varying their distances and simultaneously measuring accommodation. Benel arranged to do this and also to measure the apparent size of a foveally presented collimated disc as a function of such manipulations. But first it was necessary to validate the appropriateness of the slope of the regression of accommodation on stimulus distance as a psychophysical (as opposed to a physical) index of stimulus adequacy. Textural stimuli that ranged from sharply imaged gratings to grossly blurred images of the same targets were presented at varying optical distances.

An Index of Stimulus Adequacy

As illustrated in Figure 10, stimuli were positioned in the collimated portions of the optical channel between lenses L3 and L4, and L5 and L6, respectively. Movement of the stimuli within each channel varied the optical distances independently. Lenses L3 through L6 are of 180 mm focal length yielding a maximum dioptric power for each channel of 5.56 D and equal magnification within each channel. The diameter of the circular stimulus field subtended a visual angle of 12 degrees. The size was limited by a field stop (FS2) placed at -5.56 D (beyond optical infinity). The field stop provided a severely out-of-focus edge image that would not act as an accommodative stimulus.

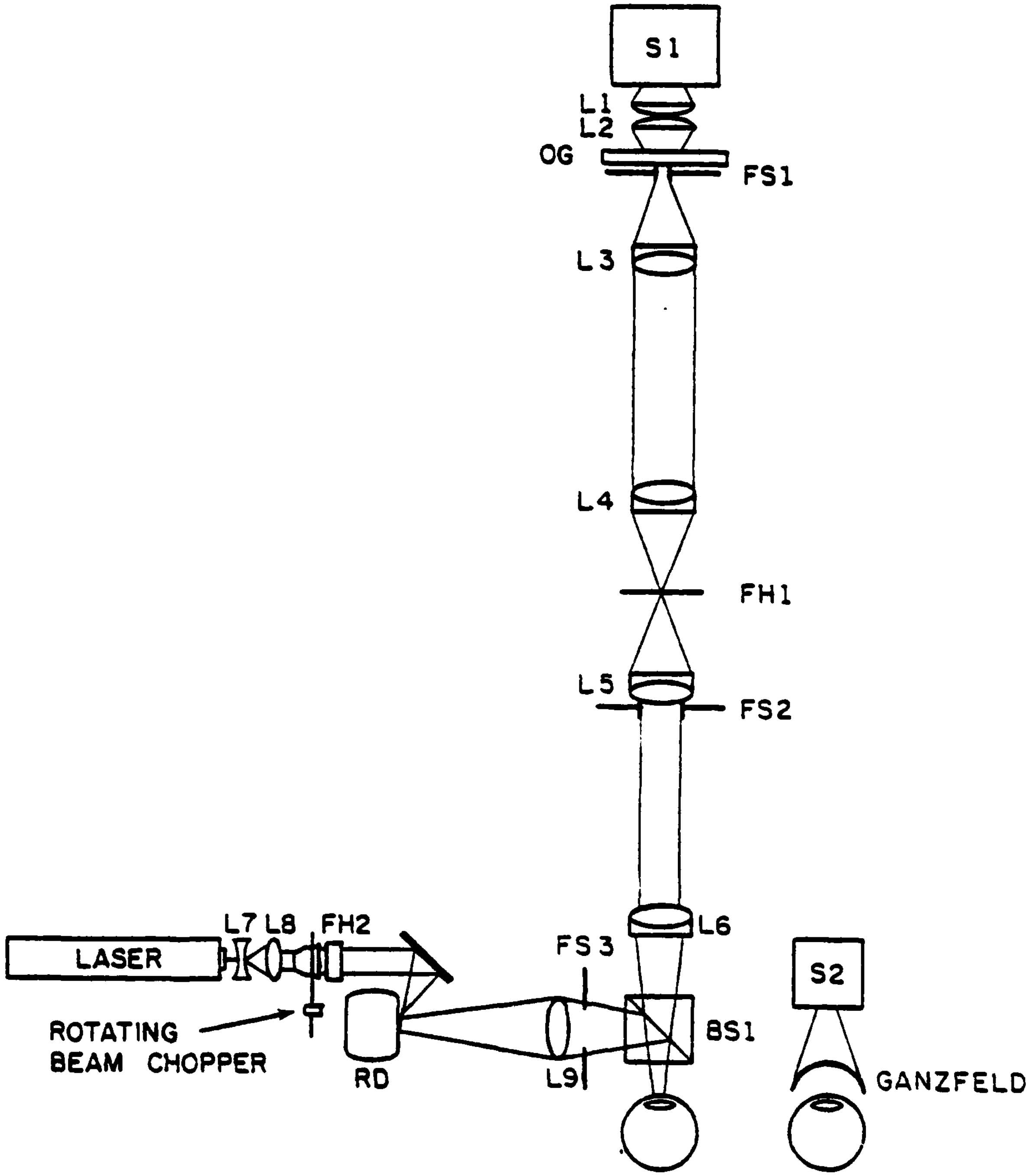

Figure 10. Schematic diagram of the Maxwellian viewing system and the accommodation measurement apparatus used by Benel (1979).

Results of Benel's first experiment are summarized in Figure 11. Accommodative responses to Screen 1 (the high-contrast grating) were reasonably accurate, approaching a slope of 1.0, throughout the range of stimulus presentation distances. With successively defocused gratings (Screens 2, 3, and 4), accommodation lapsed toward the dark focus, and the regression slopes flattened accordingly. Comparison of the accommodative regression slopes and the objective changes in stimulus characteristics (percent contrast) supports the validity of this metric as a functional (psychophysical) description of stimulus adequacy.

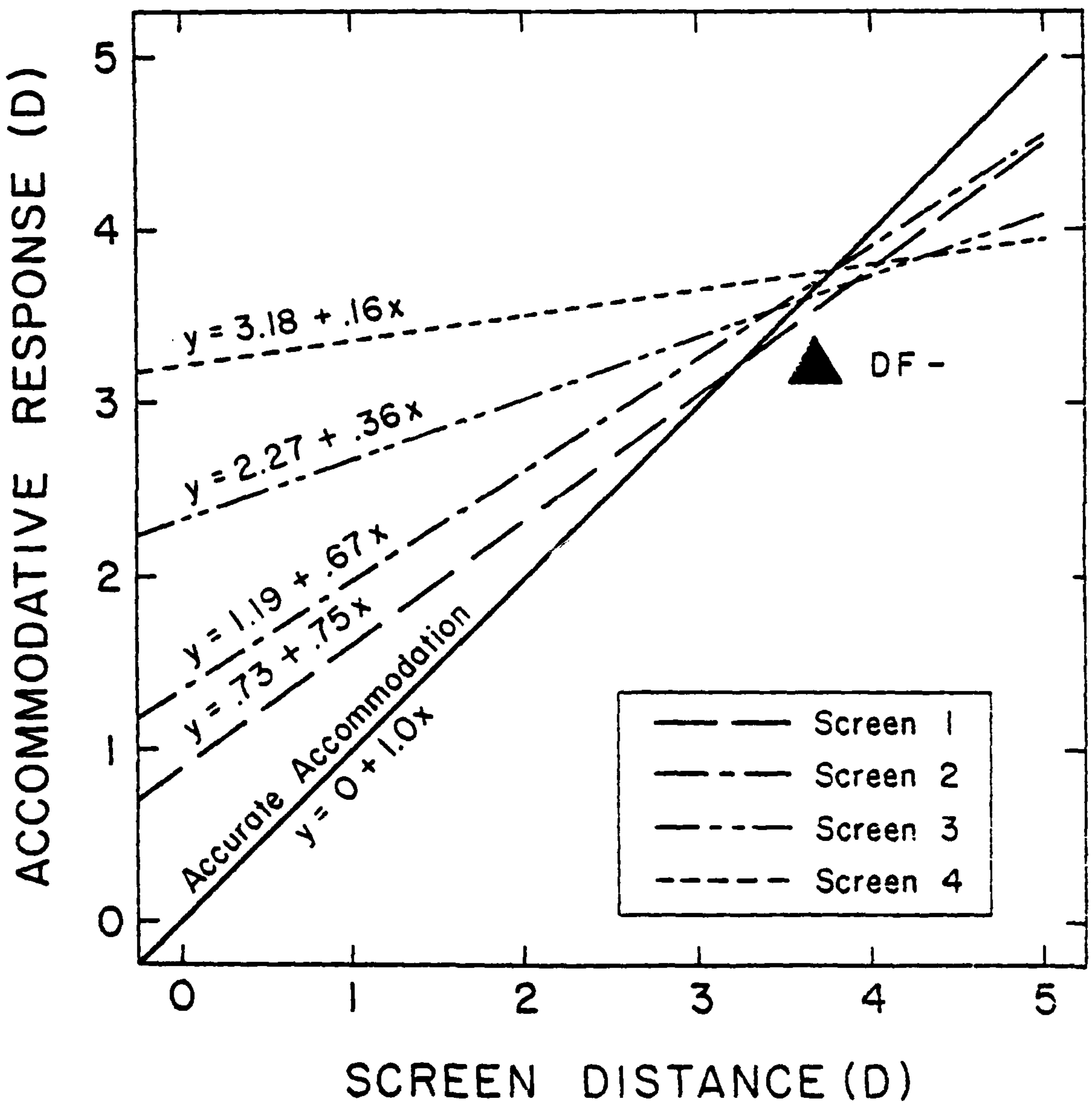

Figure 11. Regression of accommodation on stimulus presentation distance for each of four gratings varying in contrast ratio from high (Screen 1) to low (Screen 4) tested by Benel (1979).

Refining the Mandelbaum Effect

In his second experiment, Benel investigated the possibility, noted by Owens, that changes in the retinal image with changes in the observer's position could have confounded Mandelbaum's findings. The four screens of varying contrast were presented at varying optical distances while subjects attempted to resolve high-contrast acuity targets (matrices of Snellen Es of varying orientation) also presented at varying distances. The effects on accommodation of target distance, screen distance, and screen contrast and their first-order interactions were all reliable. Target distance accounted for 61 percent of the response variance, and the various effects of screens, screen distances, and their interactions accounted for an additional 20 percent.

For the two high-contrast screens (1 and 2) the effect of screen position on accommodation was quite evident. As screen position approached the individual's dark focus, the screen tended to draw accommodation away from the targets' distance. Under certain circumstances the high-contrast screens provided more potent stimuli than the matrix of Es. For example, when the target was at 3.75 D and either Screen 1 or 2 was more distant, accommodation was drawn outward. However, neither Screen 3 or 4 exerted a similar influence.

Apparent Size and Accommodation

Hoffman's observation, quoted earlier, indicates that inward shifts in accommodation are accompanied by reductions in apparent size. As Hoffman pointed out, objective measurement of such shifts is difficult because any measuring standard (visible scale) presented with the object to be judged changes proportionately. Under such circumstances, the ostensibly objective size will remain constant despite the subjective impression of a shrunken object and scale. The converse was not discussed explicitly by Hoffman but follows logically. An outward shift in accommodation should be accompanied by an increase in size of an object and its surroundings, as demonstrated successively by the Iavecchias, Simonelli, and Hull and Gill.

In these earlier experiments at the University of Illinois, stimuli presented included irregular and unquantified textural gradients, usually in natural vistas, that allowed various types of experimental confounding in the manipulation of accommodation. If accommodation were induced by targets and competing screens of quantitatively known stimulus adequacy, the relationships between induced accommodation distances and apparent size might be purified. Calling merely for subjective judgments of "smaller," "larger," or "no change," Benel inserted screens at various optical distances as subjects fixated targets, also set at various distances. The coincidence of "smaller" judgments with inward accommodation shifts and "larger" judgments with outward shifts was statistically reliable.

Apparent Size and the Mandelbaum Effect

In all experiments involving the Mandelbaum effect as such, investigators other than Benel have been concerned mainly with measurable decrements in visual acuity associated with the inappropriate accommodation induced. To quantify shifts in apparent size with the Mandelbaum effects of varying screen distances, Benel set up a fourth experiment. Using the moon machine in an arrangement similar to that used by the Iavecchias looking east from the fifth floor of the psychology building, Benel inserted a black fiberglass windowscreen at varying distances between the subject and the recently cleaned window. Nothing was changed in the subject's view of the campus vista except the position of the screen.

As illustrated in Figure 12, reliable shifts in apparent size of the collimated moon just above the distant horizon (as indicated by the subjects' settings of the uncollimated comparison moon at one meter) were associated with the accommodation shifts induced by the screen. The correlation of -0.96 between mean judgments of size and mean accommodation levels for the 12 subjects in the six conditions was slightly higher than observed in the previous experiments involving additional stimulus variations. Approximately 50 percent of the total variance in size judgments (including subject variance) was accounted for the the inappropriate shifts in accommodation.

This finding strongly suggests a causal relationship, but whether causal or not, the practical lesson is clear: beware the dirty windshield and the head-up flight display and be cautious at night.

The Dark Focus of Accommodation: Its Existence, Its Measurement, Its Effects

In view of the emerging relationships among the dark focus, myopia and hyperopia, and perceptual responses, it was time to investigate the effects of subject populations on experimental findings. Nicholas Simonelli proposed a dissertation project that his doctoral committee reluctantly approved as a "somewhat pedestrian undertaking," in the words of Professor Lloyd Humphreys, Dean of Liberal Arts and Sciences at Illinois. But Simonelli's dissertation was hardly pedestrian. From his scholarly, entertaining, and insightful analysis of relevant literature one might suspect that what we think we know about perception is based largely on the eyeballs of college sophomores, the most readily available and near-sighted human subjects in the world.

Compared to the professional pilots tested in the studies at Ames Research Center, undergraduates in universities with stiff academic requirements are, on average, myopic to a degree exceeded only by psychology graduate students and their spouses, another popular source of subjects. The mean dark focus distances of the student subjects in the earlier studies by Simonelli, the Benels, and Hull and Gill were all well within one meter, as has typically been found in the many studies by Leibowitz and his students at Penn State. This has been true despite the usual requirement that subjects exhibit normal visual acuity (often set at 20/25 rather than 20/20 and occasionally with optical corrections).

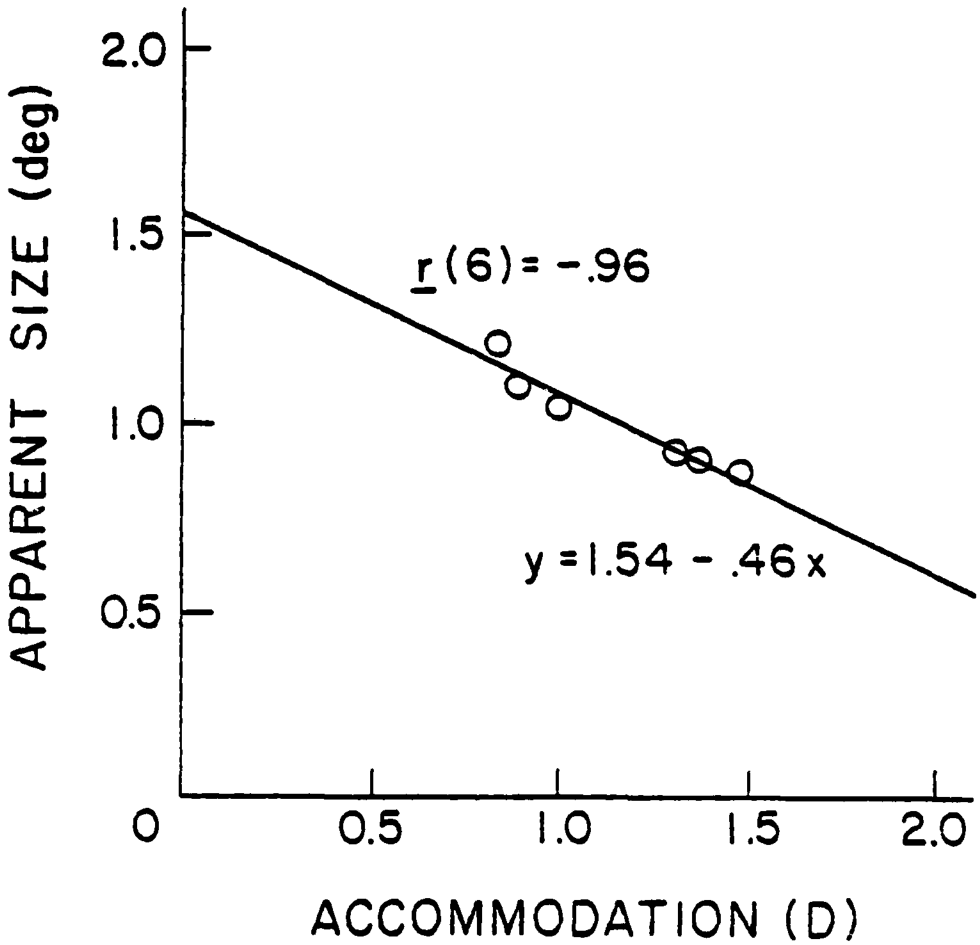

Figure 12. Apparent diameter of the collimated horizon moon over the campus vista as a function of inappropriate accommodation induced by a black mesh windowscreen interposed at optical distances of 3.0, 2.25, 1.5, and 0.75 D from the subject's eye position. Each point represents the mean size and accommodation values for 12 observers in the six viewing conditions including the four screen distances, the unscreened view, and the collimated moon with the outside view obscured. (Benel, 1979)

To study his main experimental questions, Simonelli first developed a new optometer, described earlier, that was simpler and easier to operate than the laser optometers used in the earlier experiments at Illinois. It also proved to yield slightly more repeatable measures of accommodation, but its chief advantages were its reliability of operation and its ease of explanation and use in the testing of large numbers of experimentally naive subjects, military trainees at Chanute Air Force Base as well as college students. The results of Simonelli's two main experiments using this device call for a critical reappraisal of the generality of many accepted findings in the vast literature on visual perception.

The Sampling of Eyeballs

In all, Simonelli tested 301 subjects ranging in age from 17 to 67. Of these, 114 were psychology students, and 154 were Air Force recruits of comparable ages (253 of the 268 were between 17 and 22); 33 subjects distributed over the range from 28 to 67 were neither students nor recruits. In addition to taking near point, dark focus, and far point measurements, Simonelli introduced the term "relative dark focus," the difference in diopters between an individual's dark focus and far point, the distribution of which is shown in Figure 13 for all 301 subjects combined. Separate statistics for the students and recruits are given in Table 1.

Although students and recruits did not differ reliably in terms of near point or relative dark focus on average, that was the end of the similarities. The students were almost 1.5 D more myopic than the recruits (far-point comparison), and their measured dark-focus distances were also 1.5 D closer (in centimeters, 37 versus 84). In Simonelli's words:

> These differences, especially the far points, will come as no surprise. Students are typically thought of as having poor vision and their caricatures usually include eyeglasses. Similarly, the Air Force is so associated with good vision that many would-be volunteers wrongfully self-select themselves out of the Air Force volunteer population because of their myopia. This only serves to exaggerate the difference. In other words, one would expect the recruits to have "better" vision than the students.
>
> A more subtle sampling difference, however, is seen when an ostensibly objective screening criterion is applied. If only those students and recruits are chosen whose far acuity is 20/25 or better the statistics are as shown in Table [2]. The most interesting difference is that of the far points. Because the means of the recruits' and students' far point distributions are separated by 1.5 D, limiting both distributions at one fairly extreme point (20/25 acuity) produces two new distributions with means still 0.3 D apart. This, in turn, leads to mean measured dark focuses also separated by approximately 0.3 D as shown.

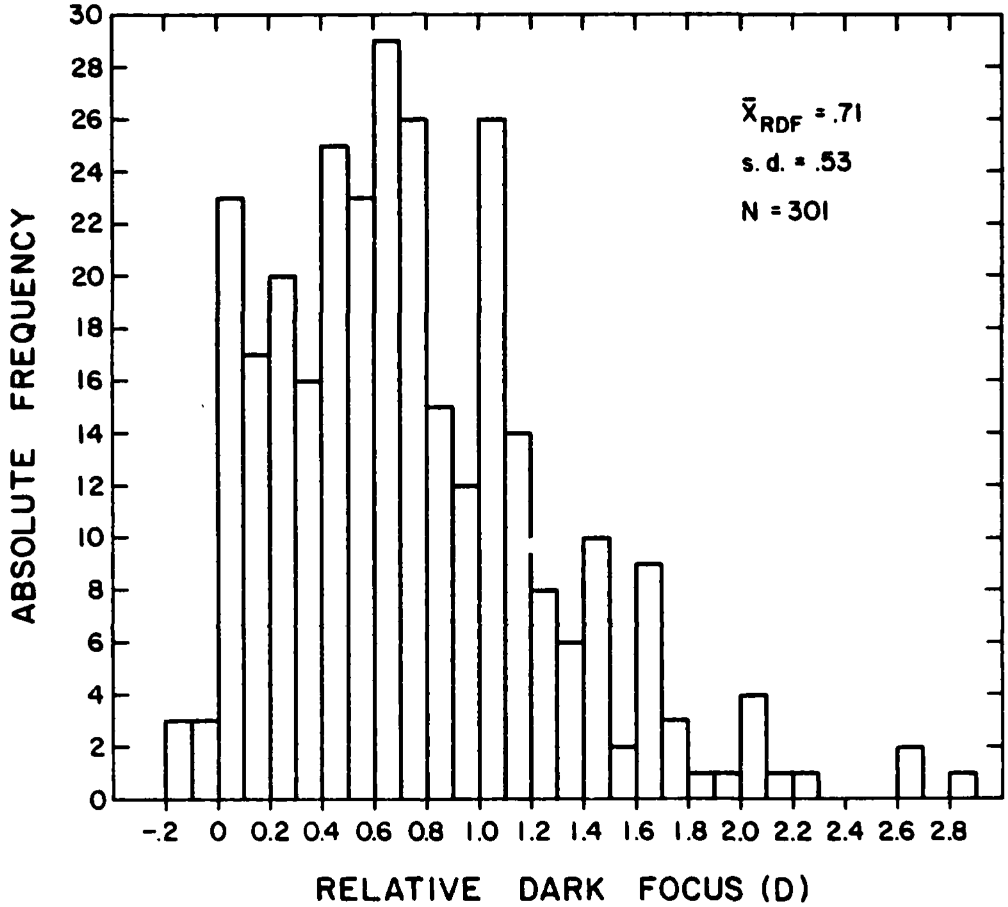

Figure 13. Distribution of relative dark focuses (Simonelli, 1979b).

Table 1

Comparison of Visual Characteristics of Psychology Students and Air Force Recruits (Simonelli 1979b)

Characteristic	N	Mean	sd	t	df	p
Far Point						
Students	114	1.918	2.39	6.27	266	.000
Recruits	154	0.471	1.37			
Measured Dark Focus						
Students	114	2.672	2.57	5.92	266	.000
Recruits	154	1.191	1.50			
Relative Dark Focus						
Students	114	.753	.56	.51	266	.612
Recruits	154	.720	.51			
Near Point						
Students	114	11.226	3.70	1.21	255	.266
Recruits	143	10.706	3.17			
Amplitude						
Students	114	9.308	3.39	-2.38	255	.018
Recruits	143	10.262	3.02			

Table 2

Comparison of Visual Characteristics of Psychology Students and Air Force Recruits After Selecting Individuals with Far Acuity of 20/25 or Better (Simonelli 1979b)

Characteristic	N	Mean	sd	t	df	p
Far Point						
Students	34	.147	.48	1.78	136	.077
Recruits	104	-0.116	.82			
Measured Dark Focus						
Students	34	.853	.54	1.55	136	.123
Recruits	104	.592	.93			
Relative Dark Focus						
Students	34	.706	.47	-.02	136	.986
Recruits	104	.708	.52			
Near Point						
Students	34	8.800	2.65	-2.62	125	.010
Recruits	93	10.179	2.62			
Amplitude						
Students	34	8.653	2.69	-3.31	125	.001
Recruits	93	10.405	2.62			

> ....Only 34 "natural" emmetropes (defined for purposes here as 20/25 or better without corrective lenses) were found among the 114 psychology students. Most likely, a proportionately small number of natural emmetropes were among the hundreds of "functional" emmetropes [myopes wearing corrections] in the Leibowitz and Owens studies, but their data cannot be separately identified. (Simonelli, 1979b, pp. 110, 112, 115)

The Effects of Age

The effects of age on the various accommodative measures are shown in an overly simplified summary form in Figure 14. It has long been known that the near point recedes with age (and the "shortening" of the arms), but the slower recession of the dark focus and far point, while suspected, has not been accurately documented previously. Although Figure 14 represents all these changes as linear functions of age, Figure 15 shows what all airline pilots have learned to expect, namely, that the onset of the outward migration of the focus for any individual tends to be noticed rather suddenly during the mid 40s.

Acuity Demands

There is an abundance of credible experimental data suggesting that the accommodative response is an antagonistic compromise between the pull of the stimulus and the pull of the dark focus. Many have speculated and some have reported anecdotal evidence that the resolution of the compromise for the individual eyeball depends largely on the fineness of the discrimination required. For example, Brian Brown of the Smith-Kettlewell Institute of Visual Sciences noted informally that tracking recordings from the Crane-Cornsweet infrared optometer shifted outward in stepwise fashion as subjects attempted to read successive lines of a Snellen eye chart across the room (personal communication).

Another example, once more in Simonelli's words:

> An intriguing finding by Iavecchia et al. (1978) was the subjects' differential accommodation to the various outdoor scenes--all at essentially 0 D. The scenes mathematically varied from 0.03-0.00 D, but this minuscule difference should not account for the gross variation observed. Was the eye actually responding to the minute changes in the dioptric distances of the scenes? Or was there some compositional aspect of the views (resulting from the masking) that elicited different levels of accommodation? That is, when nearby, larger objects are prominent, perhaps their more easily recognized details (subtending larger visual angles) identify the objects in sufficient detail so that it is not necessary to force accommodation out to 0 D. The eye may be "lazy," as it has been referred to by some.

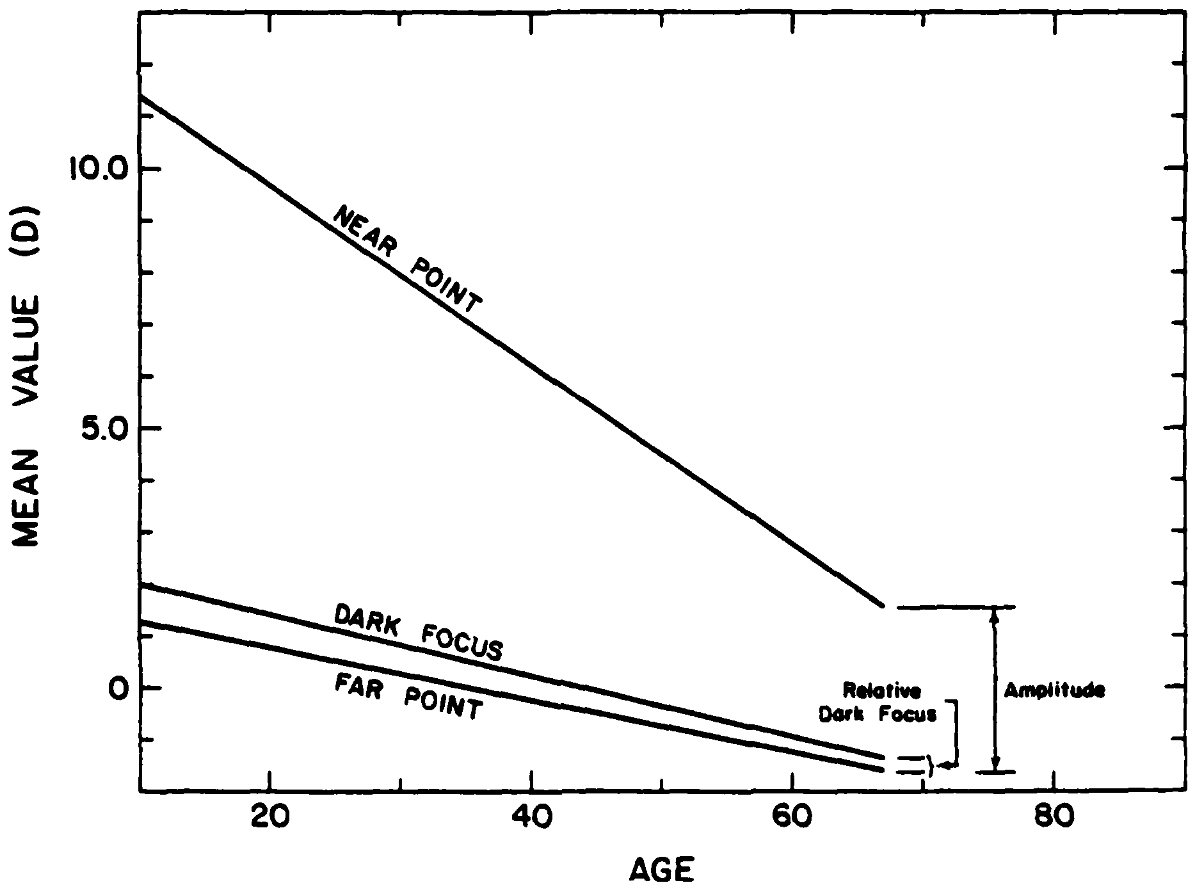

Figure 14. Basic changes in near point, far point, and dark focus with increasing age (Simonelli 1979b).

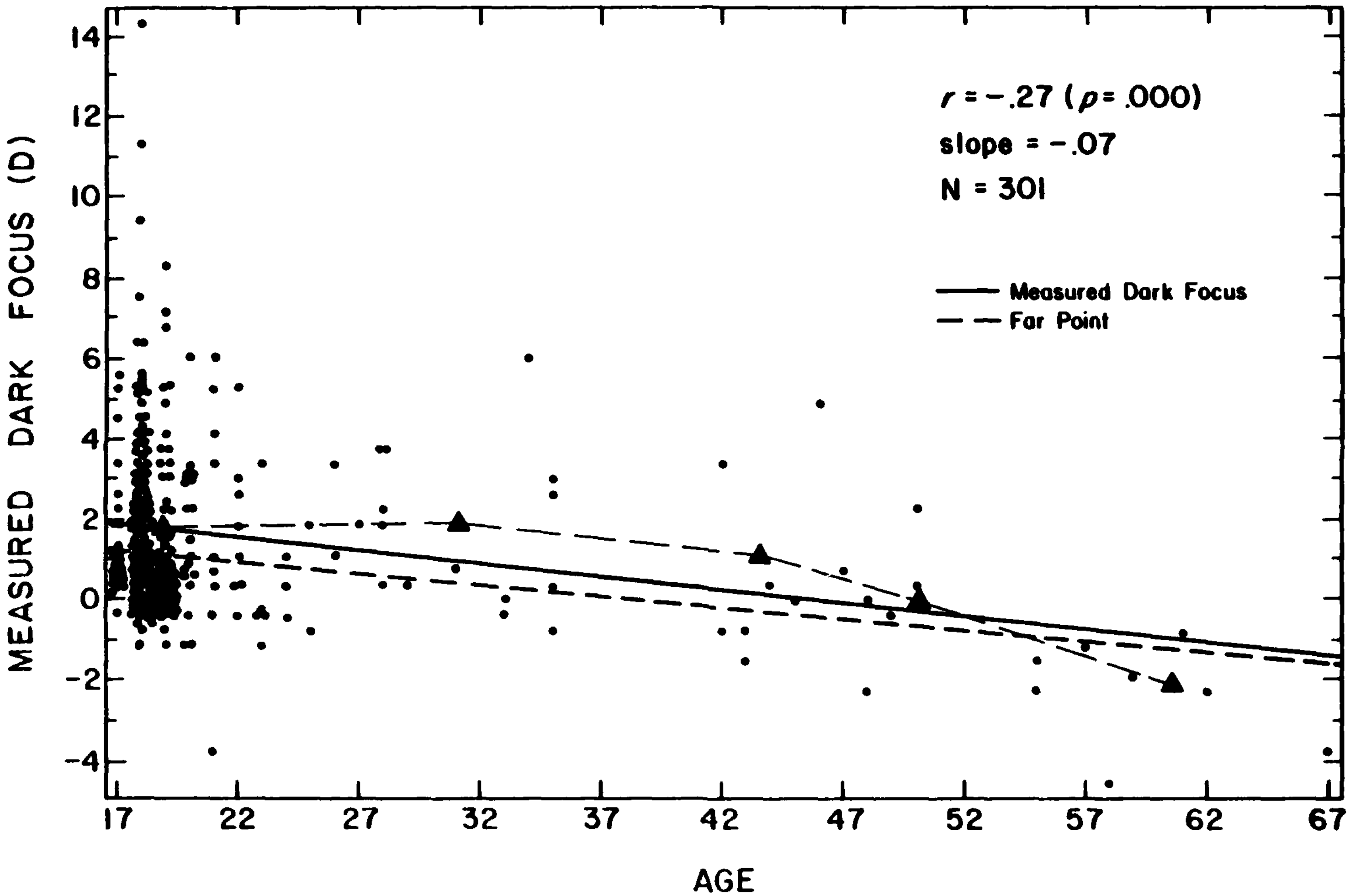

Figure 15. Relationship between measured dark focus and age showing the relatively rapid outward migration of accommodative responses during the mid 40s and thereafter. The linear regression lines for measured dark focus and far point recession with age do not accurately reflect the abruptness of the typical change for the individual.

> A response of 0.5 D to the roof of a large building 40 m away, as found in the Iavecchia study, may depend primarily on the "acuity demands" of the situation, the object of this experiment. Simply, the acuity demand of a target refers to the smallest details that must be resolved to recognize the target. Looking out an aircraft window at the blue sky does not pose much of a focusing challenge. Reading small print at a distance, however, requires more accurate focusing. What are the effects of such demands on accommodation and do these effects vary with the dark focus? (1979b, p. 72)

In Simonelli's experiment, acuity demands for accurate discrimination were varied while target distance (7.6 m) and illumination (1.3 FtL) were held constant. Targets were of two types, Snellen letters and modified Landolt Cs, as illustrated in Figure 16. Because Snellen letters vary in size as well as spatial frequency components, Landolt Cs of constant size but varying gap widths were included as an experimental control; if the Snellen letters elicited differing accommodative responses but the Cs did not, then stimulus size rather than acuity demand would appear to be the critical variable. This was not the case, and the results for the Snellen letters only are shown in Figure 17.

There were wide individual differences in the responses of the subjects, as illustrated dramatically in Figure 18, but on average accommodation shifted outward in an orderly stepwise progression until individual eyes could no longer resolve the letters and resist the inward pull of the dark focus. The confirmation of Brown's informal finding was not surprising, but the absolute values of the subjects' responses were: only the largest letters failed to pull accommodation to the distance of the target; as letters became more difficult to resolve, accommodation receded beyond the target distance. Presumably focusing at a distance greater than the target's would, if anything, reduce the clarity of the retinal image, while in fact acuity increased.

Zoom-Lens Hypothesis

Given the coincident facts that (1) accommodation shifts outward with increasing acuity demand, until resolution is no longer possible, and (2) the apparent size of targets increases disproportionately with outward accommodation, it is increasingly tempting to advance the hypothesis that outward accommodation, beyond the distance at which everything comes into clear focus, is functionally analogous to the action of a zoom lens of a television camera. More specifically, the hypothesis is that outward accommodation beyond optical infinity magnifies the retinal image, thereby causing it to impinge on a larger area of receptors and yield both finer discrimination and larger than life-size appearance.

Stimuli	Standard Snellen Rating	Stroke Width (mm)	Visual Angle of Stroke at 7.6 m (min)
F P	20/200	17.7	8.0
L P E D	20/100	8.9	4.0
T O Z	20/70	6.2	2.8
P E C F D	20/40	3.5	1.6
F E L O P Z D	20/25	2.2	1.0
F E L O P C T	20/15	1.3	0.6

Stimuli	Gap Width (mm)	Visual Angle of Gap at 7.6 m (min)
1	17.7	8.0
2	8.9	4.0
3	6.2	2.8
4	3.5	1.6
5	2.2	1.0
6	1.3	0.6

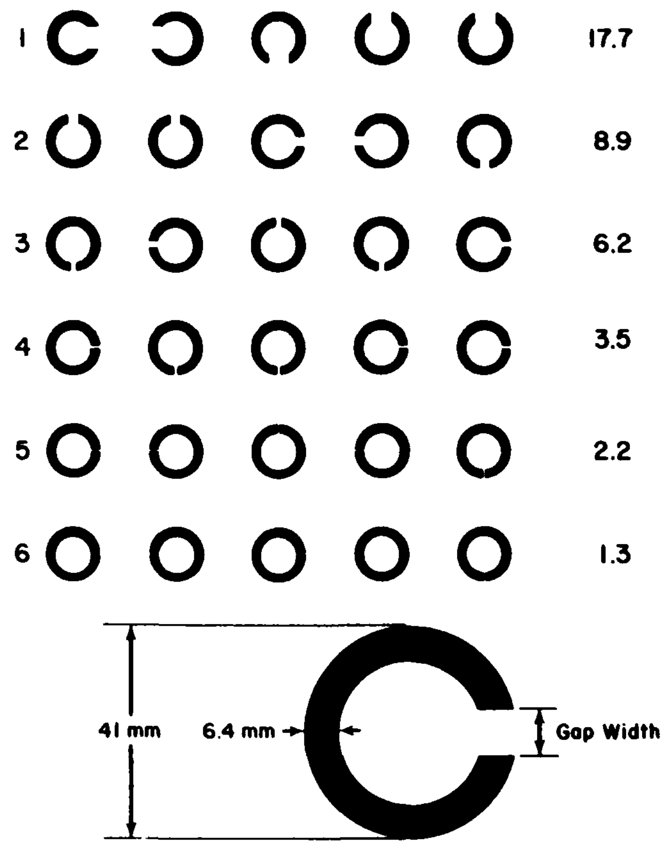

Figure 16. Snellen letters and modified Landolt Cs used by Simonelli to vary accommodative demand.

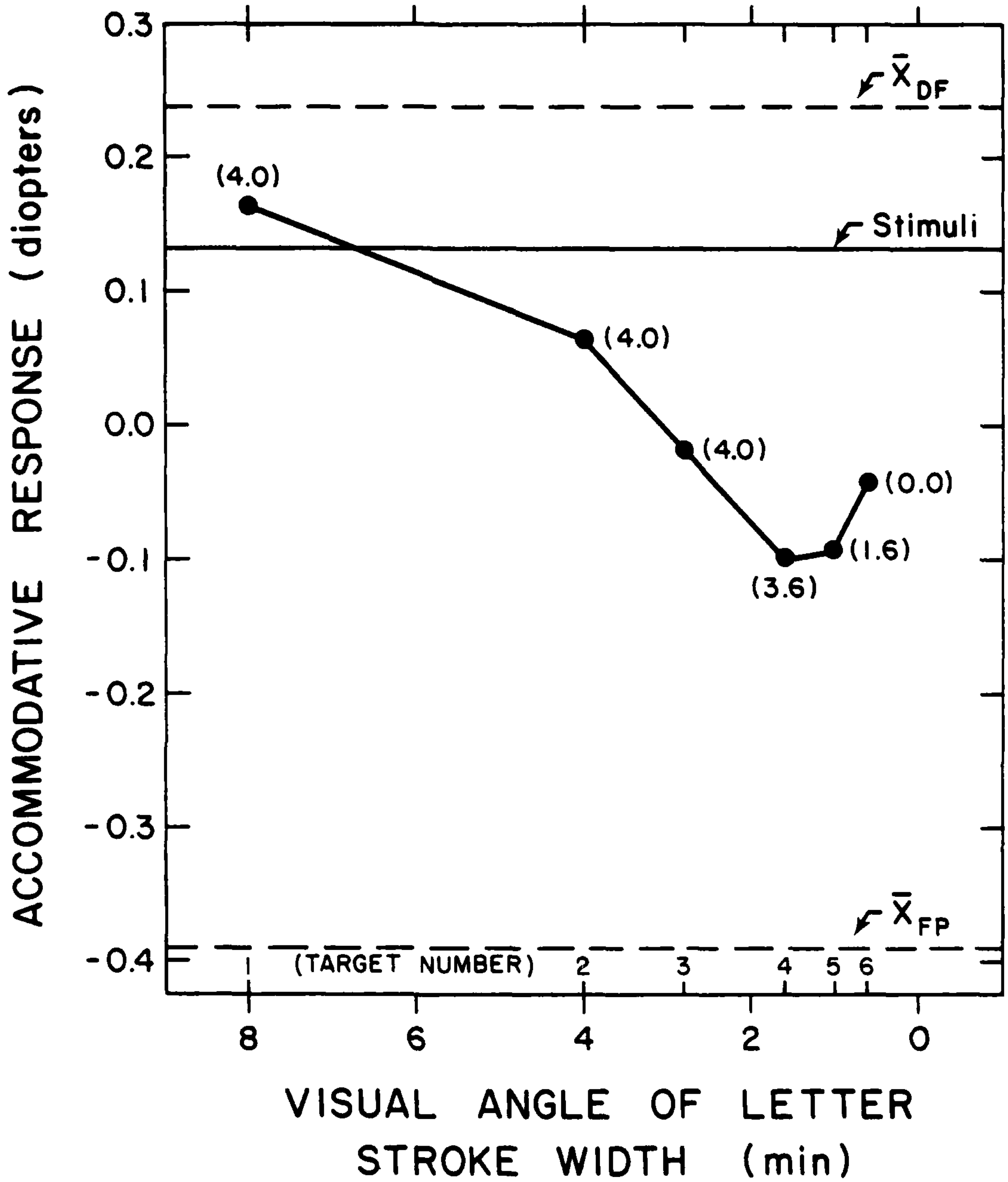

Figure 17. Mean responses to the Snellen targets. Numbers in parentheses are mean acuity scores, 4.0 representing all letters read correctly, 0.0 representing none read correctly.

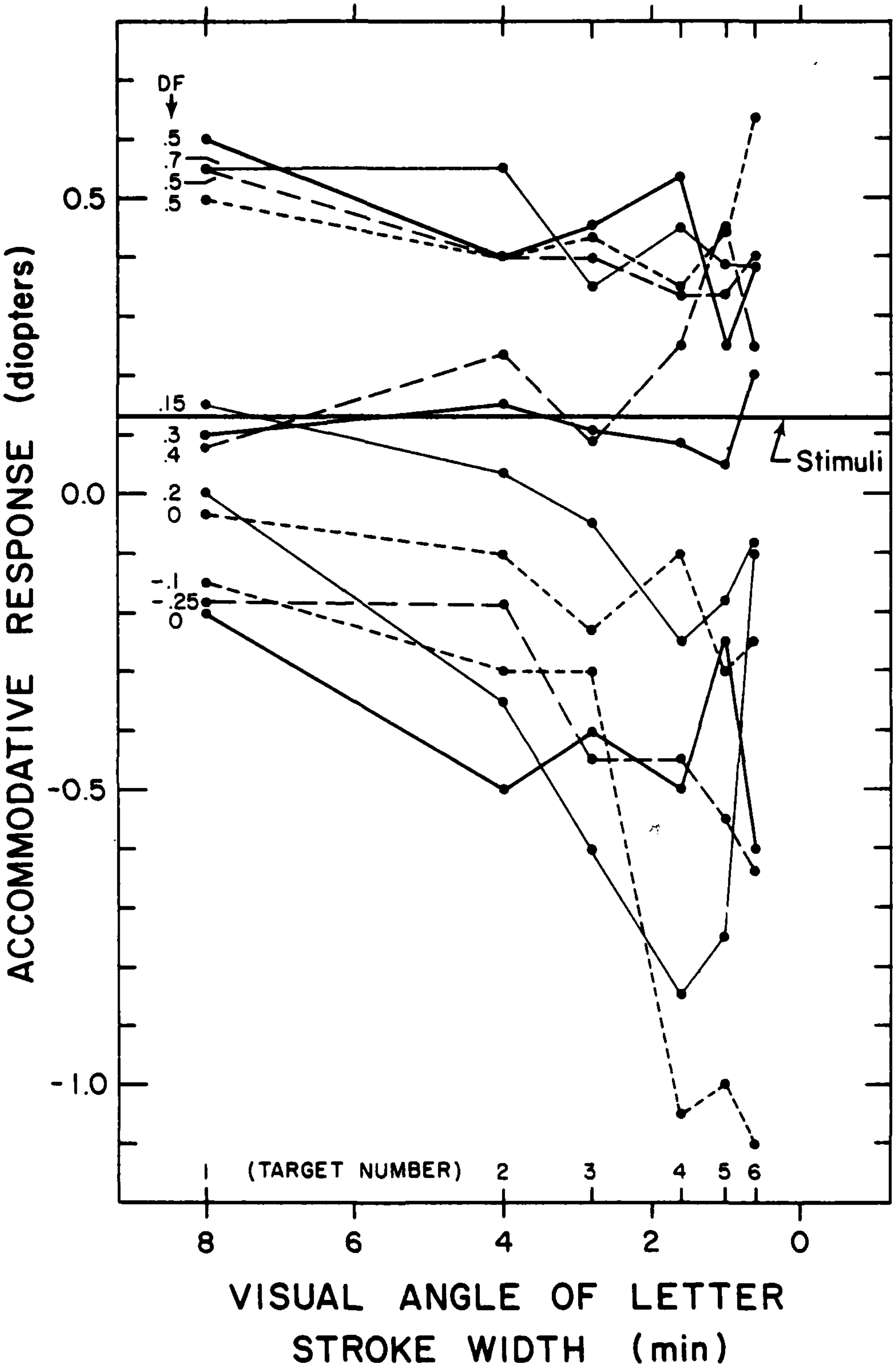

Figure 18. Individual accommodative responses to the Snellen targets showing the strong dependence of an individual's ability to accommodate beyond the stimulus distance on his or her resting accommodation distance, or dark focus (DF).

A critical test of the zoom-lens hypothesis is needed, but to date none has been reported. In my judgment the most nearly critical experiments are those dealing with the projection of afterimages, particularly those of Francis Young (1952) involving projection over large distances. Young's results would be predicted by the hypothesis, as would those of Ohwaki (1955). The assumption of invariant retinal image size with changing accommodation is essential to the validity of the model of the reduced schematic eye, but there is little support for this "null" hypothesis. To the contrary, the literature is replete with unexplained violations of size-distance invariance that would be predicted by the zoom-lens hypothesis.

The Critical Test

A critical test of a causal dependence of apparent size on accommodation distance would seem to require the independent manipulation of the latter without providing any other cues that might affect the former. A Pavlovian conditioning technique developed by Randle (1970) offers such a possibility. By using the output signal from the covert infrared tracking optometer to modulate the pitch of an audible tone, a subject can be provided nonvisual feedback of accommodative responses. As a subject learns the relationship between pitch and accommodation, the visual stimuli that initially induce accommodation can be eliminated in a classical conditioning arrangement.

A subject so conditioned accommodates to the tone with no visual cue to distance that might affect apparent size. By having subjects view the collimated virtual image of the moon machine against a dark background while accommodated to various distances, any changes in apparent size, relative to the adjustable real image of the comparison at a visible distance of one meter, would have to be caused by the aurally induced changes in accommodation. Alternatively, by a slight modification of the moon machine, afterimages can be formed while the eyes are accommodated to various distances and their sizes measured by a similar comparison procedure.

Accommodation, Personality, and Autonomic Balance

Robert Randle of Ames Research Center is among the most experienced hands-on investigators of visual accommodation and its correlates. It was he that first put me onto the importance of the autonomic nervous system in visual performance. We were studying a strip-chart recording from the Crane-Cornsweet infrared optometer when he casually commented, "This subject is obviously a sympathetic type." In the discussion that followed, Randle asserted that he could tell from a subject's behavior when he came into the lab and was introduced to the optometer what his accommodative responses would look like on the strip chart. In view of Randle's typical reluctance to speculate, his sympathetic-parasympathetic personality theory warranted more formal statement (Roscoe and Benel 1978) and systematic investigation (Gawron 1979).

Correlational Evidence

When Valerie Gawron accepted the challenge of this complex experimental problem, she soon found that Randle's informal observations had been partially anticipated by many and studied experimentally by a few, though apparently no one had actually reported correlating autonomic balance and accommodative responses. The prior work primarily involved attempts to relate indices of autonomic balance to various "personality" measures and clinically observed behavioral characteristics and, in a few cases, to intelligence and skilled performance. Indeed, Francis Young, another of the most experienced hands-on investigators of accommodation had specifically advanced the notion that intelligence and myopia are positively correlated (Young 1957).

The balance between sympathetic (SNS) and parasympathetic (PNS) branches of the autonomic nervous system has been linked to individual differences in personality by Wenger (1947; Wenger and Cullen 1972) and by Eysenck (1953), among many others. More specifically extraversion seems to be associated with SNS-dominance and introversion with PNS-dominance, which is basically what Randle had inferred. Since autonomic balance also mediates near (PNS) and far (SNS) accommodation (Cogan 1937; Olmsted 1944), the personality differences commonly attributed to near- and far-sighted people may depend upon a common underlying cause (Roscoe and Benel 1978).

Gawron's Findings

Gawron tested 152 recruits between the ages of 18 and 28 at Chanute Air Force Base during the summer of 1979. She investigated relationships among autonomic balance, refractive error, and introversion-extraversion as indicated by the Eysenck Personality Inventory. To measure autonomic balance she modified four physiological tests developed by Wenger and Ellington (1943) and processed the respiration and heart rate data to obtain an index of "weighted coherence" more recently introduced by Porges (1976). Her measures of refractive error included near point, using the RAF Near Point Rule, and dark focus and far point, using Simonelli's polarized vernier optometer.

What Gawron found was that some postulated relationships do indeed exist, as shown in Table 3, but they account for a relatively small fraction of the total response variance (except for the obviously strong interdependence of dark focus and far point). Specifically, the relationship between autonomic balance and near and far sightedness was reliably supported in the case of Porges's analytically sophisticated weighted coherence index (C_W) but was reliably contradicted by Wenger's index of autonomic balance ($\bar{A}$). This finding is puzzling in the view of the reliable correlation between $\bar{A}$ and C_W, as expected. Evidently some factor not measured or even identified is also at work.

Table 3

Correlation Matrix of Baseline Physiological and Personality Measures

	$\bar{A}$	C_w	I/E	DF	DFR	NP
$\bar{A}$ (Wenger's index)						
C_w (Porges's index)	.20*					
I/E (Eysenck)	.10	.05				
Mean Dark Focus (DF)	-.21	-.15	.03			
Dark-Focus Range (DFR)	-.01	-.06	-.16*	.07		
Near Point (NP)	-.04	-.18*	.00	.26**	-.10	
Far Point (FP)	-.18*	-.12	.06	.94**	-.03	.29**

*p < .05; **p < .01

Many investigators have noted apparently systematic relationships between autonomic and behavioral responses. Wenger (1947) emphasized the bidirectionality of such effects: autonomic responses affect behavior, and conversely behavioral events trigger autonomic responses. Porges (in press) speculates that C_w (his "weighted coherence" measure) is an index of central cognitive processing ability, and $\hat{V}$ (his measure of "vagal tone") reflects peripheral autonomic activity. Malmstrom (1978) has shown that performances of a simple information processing task causes a systematic outward shift in visual accommodation, an SNS response. The issues are: (1) Is information processing ability positively related to PNS dominance? and (2) Does task performance elicit an SNS shift in autonomic response?

Gawron addressed these issues by comparing the pre- and post-test autonomic responses of an experimental group, who performed a short-term memory task (delayed digit cancelling) for 4 minutes, with the pre- and post-rest autonomic responses of a control group. The majority of shifts in autonomic responses, including the relative dark focus as shown in Figure 19, were in the SNS direction following task performance; pre- and post-rest measures varied unsystematically in most cases. Incorrect response latencies and latency variability were reliably correlated in the predicted direction with baseline (pre-task) measures on both of Porges's indices (C_w and $\hat{V}$) but not on Wenger's index ($\bar{A}$).

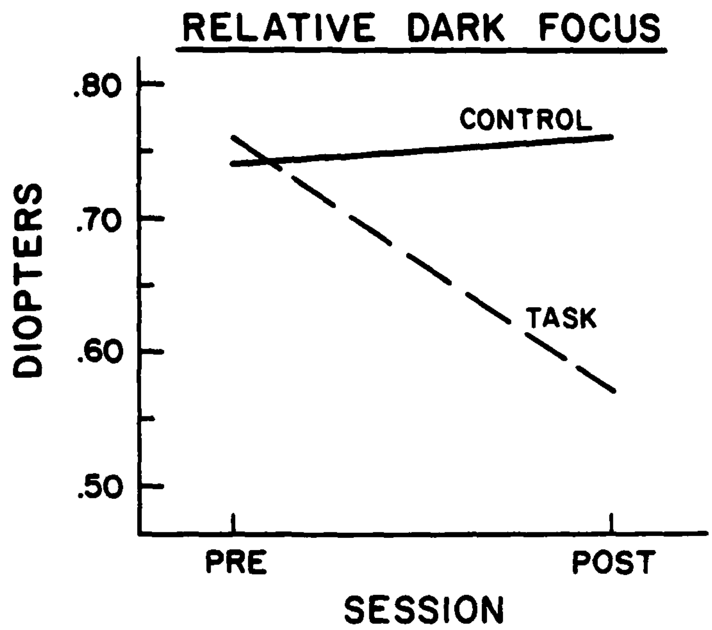

Figure 19. Relative dark focus in diopters before and after task performance (for task subjects) or rest (for control subjects).

In Gawron's words:

> Randle's hypothesis predicts that differential shifts in autonomic balance will be produced by the performance of cognitive tasks (SNS shift) versus rest and relaxation (PNS shift). Reliable SNS shifts did occur after task performance. This supports Randle's contention and replicates Malstrom's (1978) finding that task performance has an SNS effect. Application of these findings to the real world of aviation is as yet tentative but ...[the findings]... suggest the importance of future work in this area, particularly on the effects of elevated cockpit workload on pilots' approaches to landings.

FUTURE DIRECTIONS

This investigation has been concluded at the University of Illinois and has been resumed at New Mexico State University under a new grant from the Air Force Office of Scientific Research. The laboratory facilities developed under this program, including the moon machine and various optometers and cameras, were generously transferred to New Mexico State by the Department of Psychology of the University of Illinois. In addition, the Ames Research Center, NASA, has loaned New Mexico State the Crane-Cornsweet infrared tracking optometer used by Randle and his many associates. The exploratory investigations at Illinois were essential preliminaries to more systematic experiments in the continuing investigation of ground-referenced visual orientation.

ACKNOWLEDGEMENT

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